FEASIBILITY STUDY OF MAISOTSENKO INDIRECT EVAPORATIVE AIR COOLING CYCLE IN IRAN

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ABSTRACT

This paper presents energy and exergy analysis of air cooling cycle based on novel Maisotsenko indirect evaporative cooling cycle. Maisotsenko cycle (M-cycle) provides desired cooling condition above the dew point and below the wet bulb temperature. In this study, based on average annual temperature, The Iran area is segmented into eleven climates. In energy analysis, wet-bulb and dew point effectiveness, cooling capacity rate and in exergy analysis, exergy input rate, exergy destruction rate, exergy loss, exergy efficiency, exergetic COP and entropy generation rate for Iran's weather conditions in the indicated climates are calculated. Moreover, a feasibility study based on water evaporation rate and Maisotsenko cycle was presented. Energy and exergy analysis results show that the fifth, sixth, seventh and eighth climates are quite compatible and Rasht, Sari, Ramsar and Ardabile cities are irreconcilable with the Maisotsenko cycle.

Keywords*:* Energy and Exergy Analysis - Maisotsenko Cycle – Evaporative cooling

1 INTRODUCTION

Evaporative cooling systems based on water evaporation into air are practical cooling systems which are appropriate for use in dry and hot climates. The main difference between the direct and indirect evaporative cooling systems can be found in the output product air quality. As figure 1 illustrates it indirect evaporative cooling system provides desired cooling condition without moisture.

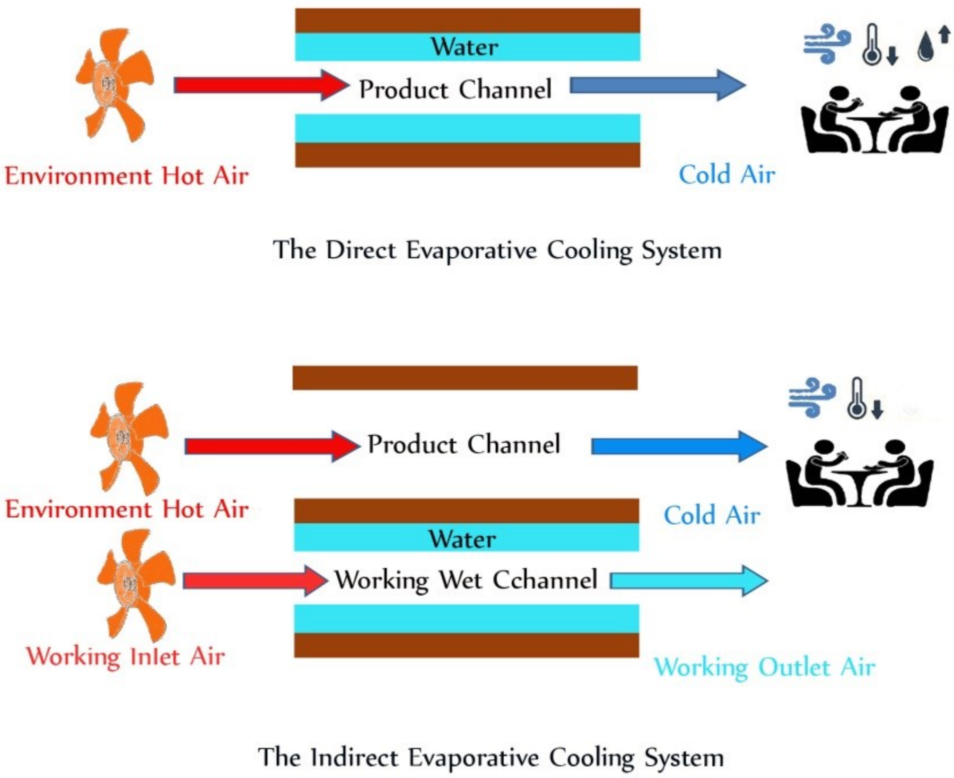

Figure 1 Diagram of the direct evaporative cooling system vs. indirect evaporative cooling system.

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Due to the proper performance of these systems, the study of their energy usage optimization was made; one of the newest kinds of these systems is the M-cycle which was introduced by Dr. Valeriy Maisotsenko[1]. The idea of use of regular perforations lead to creation of better airflow condition. The M-cycle (also called dew point evaporative cooling cycle) provides cooling condition from dew point up to wet bulb temperature of the air[2, 3]. Diagram of Principle of functioning of the M-cycle is shown in figure 2.

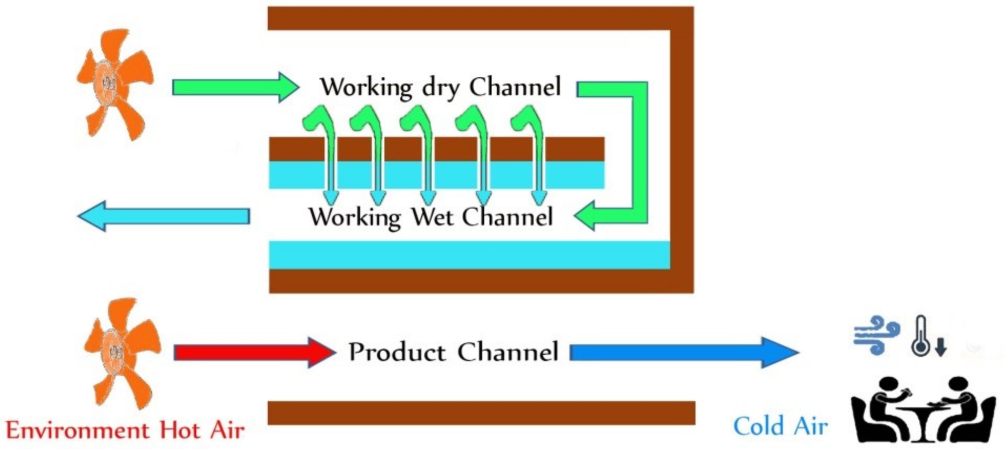

Figure 2. Diagram of M-cycle working procedure

Due to high efficiency of the M-cycle the greenhouse emissions will be decreased[4] and this process is more economic in comparison with traditional methods of cooling system [5, 6]. The maximum exergy loss occurs at 0˚C and it will reach the minimum at higher temperatures[7] so the M-cycle is more efficient when used in hot and dry climates. On the other hand due to humidity effect on the cycle performance, the cycle is not recommended to be use in humid climates[8].An experimental work reported by Zube and Gillan [9] measured influence of the mean physical effective parameters on indirect evaporative cooling system. Performance assessments of the M-cycle with energy and exergy analyses were studied by Caliskan et all. in [10, 11]. A one dimensional mathematical model developed by Anisimov and Pandelidis[12] shows the importance of climate condition on the cycle performance. Recently in their novel numerical study[13] the effective inlet variations on the m-cycle performance is investigated.

In this study, based on average annual temperature, the Iran climate is segmented to eleven climates and then, by means of water evaporation rate as well as energy and exergy analysis, feasibility of the M-cycle system in the segmented Climates is investigated.

2 ANALYSIS

2.1 Energy Analysis

The wet-bulb effectiveness as a criterion for the Maisotsenko cycle performance and The dew point effectiveness can be explained as equations (1) and (2): [10, 11]

$$\epsilon_{wb} = \frac{T_i - T_o}{T_i - T_{wb,i}} \tag{1}$$

$$\varepsilon_{dp} = \frac{T_i - T_o}{T_i - T_{dp,i}} \tag{2}$$

The coefficient of performance (COP) of the system can be found to be [11]:

$$COP = \frac{\dot{m}_o(h_i - h_o)}{\dot{W}_{blower}} \tag{3}$$

2.2 Exergy Analysis

The exergy balance can be expressed as:

$$\dot{EX}_{\mathrm{i}} = \dot{EX}_{\mathrm{o}} + \dot{EX}_{de} + \dot{EX}_{l} \tag{4}$$

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The work presented by Caliskan et al. [11] presents the terms of equations (4) which can be summarized as:

$$\dot{EX}_{\mathrm{i,dry\ air}} + \dot{EX}_{\mathrm{i,water}} = \dot{EX}_{\mathrm{o}} + \dot{EX}_{de} + \dot{EX}_{l} \tag{5}$$

$$\dot{m}_{\mathrm{dry\ air}} e_{\mathrm{dry\ air}} + \dot{m}_{\mathrm{dry\ air}} \omega_i e_{water} = \dot{m}_{dry\ air} e_{total} + \dot{EX}_{de} + \dot{Q}_{cooling}\left(1 - \frac{T_{ds}}{T_i}\right) \tag{6}$$

Exergy destruction rate ($\dot{EX}_{de}$) can be calculated by equation (6) and then the Entropy generation can be calculated as follows [10, 11]:

$$\dot{S} = \frac{\dot{E}X_{de}}{T_{ds}} \tag{7}$$

The exergy efficiency and the exergetic coefficient of performance of the M-cycle respectively are defined as [10, 11]:

$$\eta_{ex} = \frac{\dot{EX}_o}{\dot{EX}_i} = \frac{e_{total}}{e_{dry\ air} + \omega_I e_{water}} \tag{8}$$

$$COP_{ex} = COP\left(1 - \frac{T_{ds}}{T_i}\right) \tag{9}$$

2.3 Feasibility Index

The Feasibility Index, which can be used as a criterion for the evaporative cooling performance is expressed as [14]:

$$FI = 2T_{wb,i} - T_{db,i} \tag{10}$$

The small FI indicates better cooling performance in comparison with the higher value. Watt's [15] recommendations about "FI" index are shown in table 1 [14]:

Table 1: Watt [15] recommendations about "FI" index.

FI index	Watt [15] recommendation
$FI < 10$	Comfort cooling
$10 < FI < 16$	Relief cooling
$FI > 16$	The evaporative cooling systems usage is not recommended

Due to disregarding the dew point temperature, Table 1 assumed as a criterion for feasibility of direct evaporative cooling systems. In this study the value of temperature difference between the dry bulb and dew point temperature uses as a criterion for feasibility of M-cycle (FI_{dp}). According to the ref.[2], the temperature difference between the dry bulb and dew point temperature must be above 6 degrees (or Fahrenheit) for compatible use of the M-cycle.

2.4 Water Evaporation Rate

The water consumption of indirect evaporative cooling systems can be calculated by the following formula: [10]

$$V_{water} = \frac{1000 V_{wc} \rho_{wc}}{\rho_{water}} \left(w_{wc,o} - w_{wc,i}\right) \tag{11}$$

In this study the water evaporation rate is introduced as a criterion for better performance of the M-cycle because in similar condition in FI_{dp} Index, the lowest Water Evaporation Rate is preferred due to lower energy.

3 DEVELOPING A CLIMATE MODEL FOR IRAN

Iran is located in the northern hemisphere between 25° and 40° latitudes and most of its regions are situated at the height above 4500m height. This geographical condition necessarily leads to creation of temperate weather condition for Iran, but due to existence of the Alborz and Zagros Mountains, dry and arid region is created in the center and east of Iran. The difference of 15° latitude and of more than 2500m difference in height between the Iran's climates leads to creation of various weather conditions in Iran. For investigation of effective factors for developing a climate model for Iran, related information such as dry temperature, relative humidity, rainfall data, Solar radiation and winds condition which are reported by weather stations is indispensable.

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Several methods exist for development of a climate model for Iran. In this work the model is developed according to the ref. [16]. In this method to using average annual temperature difference, rainfall and evaporation rate, as well as isotherm, isohyet and evaporation representing lines and annual reports of meteorological organization in last fifteen years, Iran is segmented to eleven climates which are presented in table 2.

Table2. The Iran's segmented climates in this study.

Climate Number	Location	average annual temperature
1	The area between Alborz Mountains and Caspian Sea	15°C - 18°C
2	North of Khorasan Province and some areas of Semnan and Golestan Provinces	12°C - 15°C
3	The north west of Iran including of Ardabil, East Azerbaijan and West Azerbaijan Provinces	11°C - 13°C
4	West of Iran, west heights of Zagros Mountains which are located in Chaharmahal Bakhtiari and Kohgiluyeh Provinces and some areas of Khozestan Province	11°C - 17°C
5	West south of Iran consist of Khozestan and Ilam Provinces which is affected by warm and dry air mass of Saudi Arabia	19°C - 25°C
6	The seaside of south of Iran which consists of Boshehr, Hormozgan and south of Sistan and Balochestan Province	23°C - 28°C
7	Sistan and Baluchestan Province except the south areas and south of Kerman Province	18°C - 27°C
8	South of Khorasan Province and some regions of Semnan Province with low rainfall and rather high temperatures	14°C - 17°C
9	Semnan, Tehran, Qazvin, Zanjan,Markazi,Isfahan and Chaharmahaal Bakhtiari Province areas which are located in the south of the Alborz Mountains and east of the Zagros Mountains.	12°C - 18°C
10	West, north and south side of Sahara which created a very warm and dry climate	20°C - 16°C
11	Central salt pans of Iran have arid weather condition	19°C - 23°C

3.1 Statistical Information

The parameters of weather information related to some of the main cities of Iran are shown in table 3 which is extracted from information of Iran's meteorological organization. This table can be used for water vaporization rate and feasibility studies.

Table 3. Weather information of some main cities of Iran

City (Province)	Climate Number	Relative Humidity	$t_{dp,i}$	$t_{wb,i}$	$t_{db,i}$
Abadan (Ahvaz)	5	61 %	23.9	28	47.7
Isfahan (Isfahan)	9	25 %	5.7	19.7	38.3
Ahvaz (Ahvaz)	5	24 %	12.6	28.4	48.5
Bandar Abbas (Hormozgan)	6	68 %	27.1	30	39.8
Tehran (Tehran)	9	26 %	7.4	18.9	39
Tabriz (East Azerbaijan)	3	36 %	8.2	18.9	36.5
Shahr kord (Chaharmahal Bakhtiari)	4	31 %	5.8	16.8	34.8
Shiraz (Fars)	4	24 %	5.8	19.5	39.1
Zahedan (Sistan and Baluchestan)	7	21 %	3.4	19.7	39.5
Kerman (Kerman)	10	19 %	1.1	17.9	38
Kermanshah(Kermanshah)	4	23 %	3.6	18.8	39.8
Gorgan (Golestan)	2	65 %	20	24	36
Mashhad (Razavi Khorasan)	2	35 %	8.7	18.8	37.3

City (Province)	Climate Number	Relative Humidity	$t_{dp,i}$	$t_{wb,i}$	$t_{db,i}$
Ilam (Ilam)	5	19 %	2.9	17	30.3
Sari (Mazandaran)	1	75 %	21.3	24	26.4
Sanandaj (Kurdistan)	4	25 %	4.6	18	28.8
Yasuj (Kohgiluyeh and Boyer Ahmad)	4	25 %	4.6	16	27.1
Arak (Markazi)	9	28 %	6	17	27.5
Urmia (West Azerbaijan)	3	48 %	11.2	18.3	23.9
Ardabil (Ardabil)	3	68 %	12.2	18	19
Birjand (South Khorasan)	8	22 %	3.7	16.3	28.5
Zanjan (Zanjan)	9	41 %	8.7	17.8	24.4
Semnan (Semnan)	11	26 %	9.9	20	32
Qazvin (Qazvin)	9	38 %	10	19	27.3
Ghom (Ghom)	9	23 %	7	18.4	32.2
Hamedan (Hamedan)	4	36 %	7.8	17.3	25.5
Ramsar (Mazandaran)	1	80 %	21.4	24.1	25.3
Rasht (Rasht)	1	76 %	20.7	24	25.9

3.2 Results of the M-cycle analysis

The main Characteristics of the M-cycle are shown in table 4, furthermore, the results of this study analysis in comparison with the work presented by Caliscan et al. [11] are shown in table 5. These prepared results are related to the fifth climate with 25ºC environment temperatures.

Table 4. Characteristic of the M-cycle[11]

Characteristic	Value
inlet air temperature (environment temperature)	25˚C
outlet air temperature	13˚C
mass flow rate(air)	0.074833 kg/s
mass flow rate (water)	0.000898 kg/s
humidity ratio of inlet air	0.012 kg/kg
special heat of dry air	1.003 kJ/kg·K
environment pressure	1 bar
special heat of water vapor	1.872 kJ/kg·K
specific ideal gas constant (air)	0.287 kJ/kg·K
specific ideal gas constant (water)	0.4615 kJ/kg·K
saturated water vapor supply pressure	1 bar

Table 5. M-cycle results at (25˚C) environment temperature

Parameter	Results in this study	Results of Caliscan et al. [11]
wet bulb effectiveness	109.1 %	115 %
dew point effectiveness	75 %	78 %
cooling capacity	693.4 W	636 W
coefficient of performance (COP)	2.512	2.3
exergetic coefficient of performance (COP_{ex})	0.3378	0.3461
exergy efficiency	14.11 %	13.93 %

4 RESULTS

The results obtained from average annual temperature in eleven segmented climates of Iran which is considered as inlet temperature of the M-cycle and from the M-cycle parameters from table 3, are shown in several following diagrams.

In the energy analysis the main parameters including cooling capacity, COP wet-bulb and dew-point effectiveness for all eleven indicated climates were obtained which are shown in Figure 3. As Figure 3 illustrates, in the 5th, 6th 7th and 11th climate the M-cycle is suitable for use due to higher cooling capacity, dew-point effectiveness and primary energy ratio and lower wet-bulb effectiveness in comparison with other climates.

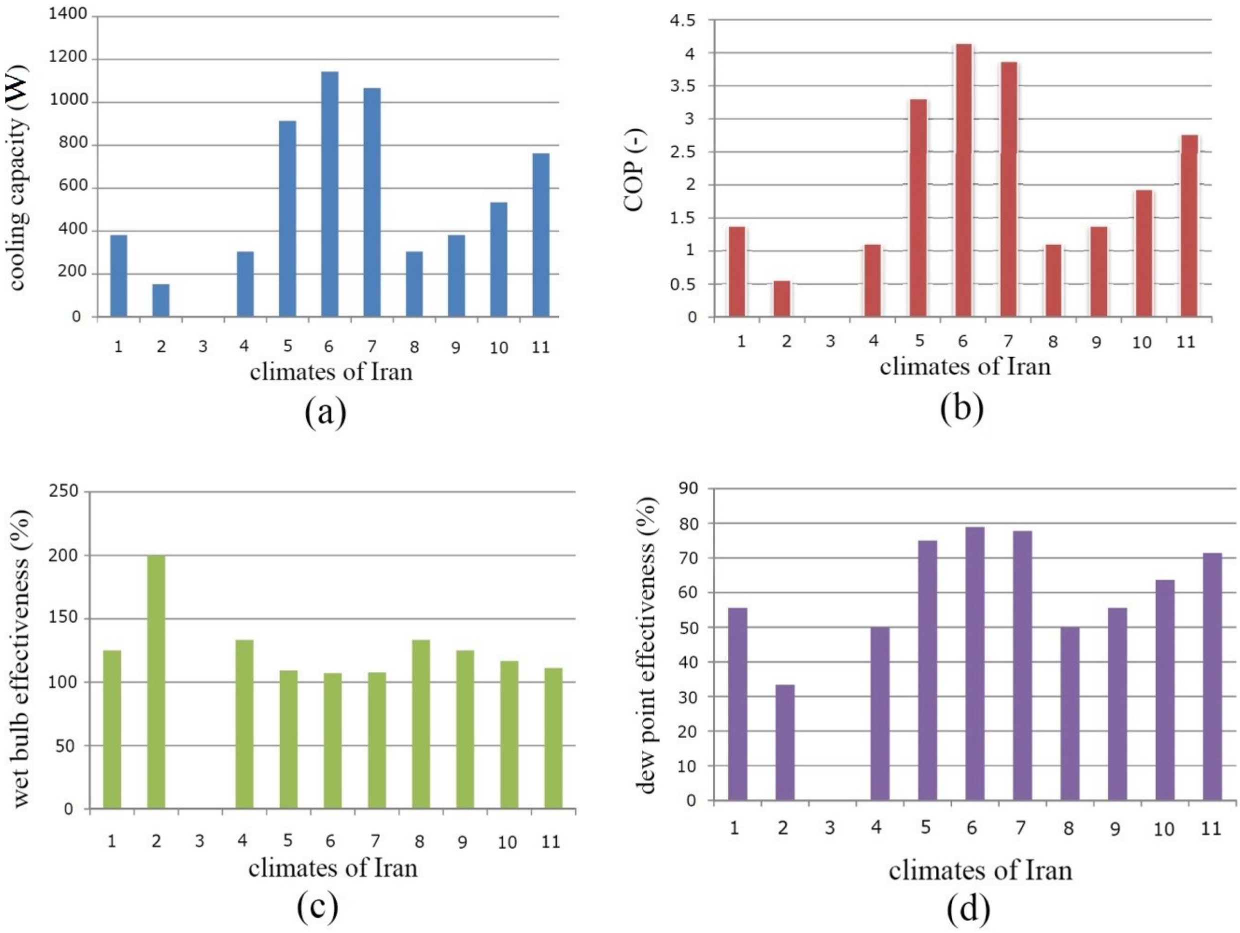

Fig. 3 The M-cycle energy analysis results in climates of Iran: (a) The cooling capacity results, (b) The M-cycle COP results, (c) The wet bulb effectiveness results and (d) The dew point effectiveness results.

The variations of the wet-bulb effectiveness with different exchanger inlet air temperatures are shown in Figure 4 (a). The range of inlet temperature is 20ºC-40ºC. Wet-bulb effectiveness can be higher than 100 % and it shows the ability of the M-cycle to cool air down to the wet-bulb temperature. At 25°C the wet bold effectiveness is 109.1 %.

The variations of dew-point effectiveness with different inlet temperatures are shown in Figure 4 (b). As Figure 4(b) shows it, the dew point effectiveness is directly proportional to the inlet air temperature and wet-bulb effectiveness is inversely proportional to the inlet air temperature. At the environment temperature (25˚C) the dew-point effectiveness is 75 %.

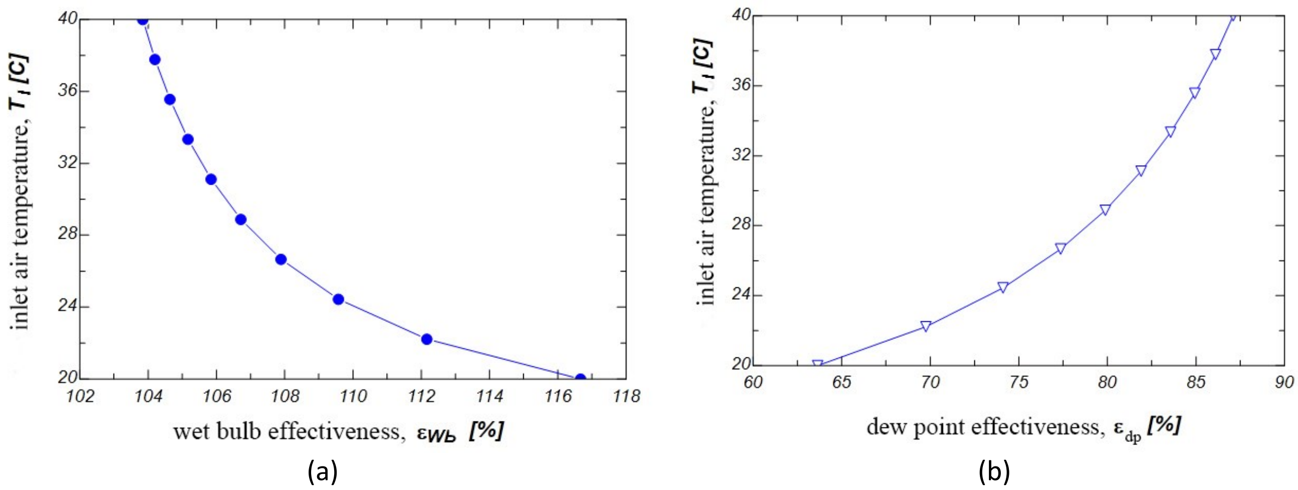

Fig. 4 (a) variations of the wet bulb effectiveness at different exchanger inlet air temperatures and (b) variations of the dew point effectiveness at different exchanger inlet air temperatures

The variations of the M-cycle COP at different inlet temperatures are shown in Figure 5. This figure shows that COP is directly proportional to the inlet temperature. At 25°C and 37°C the COP values are calculated to be 2.512 and 6.627 respectively.

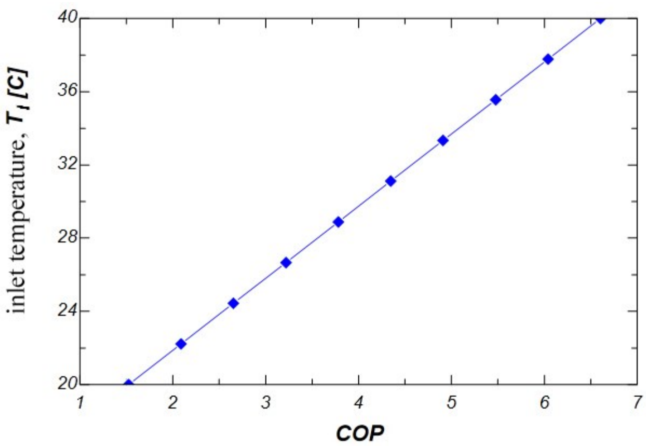

Fig. 5 variations of the M-cycle COP at different inlet temperatures.

The variations of cooling capacity at different inlet and output dry bulb temperatures are shown in Figure 6. This figure shows that cooling capacity is directly proportional to the inlet dry bulb temperature and inversely is proportional to the output dry bulb temperature.

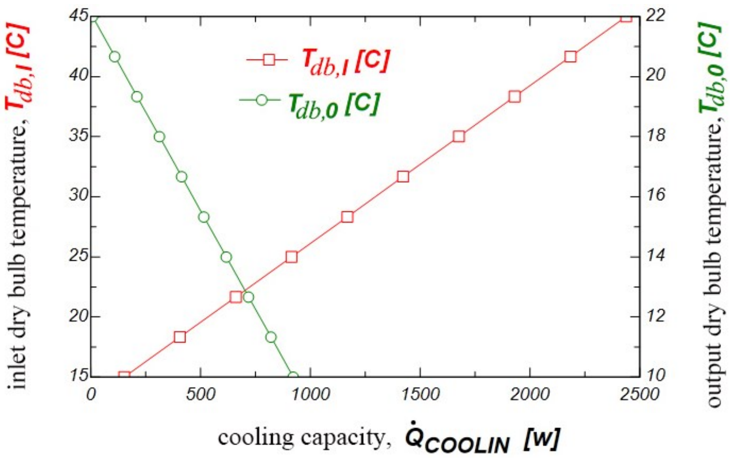

Fig. 6 variations of the cooling capacity with different inlet and output dry bulb temperatures

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Table 6 shows that the 5th, 6th, 7th and 11th climates have higher exergy efficiency in comparison with other climates. These climates have also higher entropy generation rate and lower exergetic COP in comparison with other climates.

Table 6. M-cycle exergetic analysis results for climates of Iran

Climate(s) number	Input exergy rate (W)	Output exergy rate (W)	Exergy loss rate (W)	Exergy Destruction rate (W)	Exergy efficiency (%)	COP (-)	Entropy production rate $\left(\frac{J}{kg \cdot K}\right)$
1 and 9	232.5	20.74	144.3	67.39	8.923	0.523	0.2316
2	239.7	21.73	166.2	51.75	9.066	0.623	0.1797
3	246.5	24.41	180.8	41.28	9.9	0.6552	0.1443
8 and 4	234.5	20.67	151.6	62.18	8.816	0.5494	0.2144
5	119.3	32.34	93.23	103.7	14.11	0.3378	0.3479
6	233.7	43.18	71.33	119.2	18.48	0.2584	0.3958
7	231.8	39.18	78.63	114	16.9	0.2849	0.38
10	229.6	22.08	129.7	77.79	9.617	0.4701	0.2655
11	228.2	27.06	107.8	93.35	11.86	0.3907	0.3154

In accordance with the exergy analysis, the variations of the M-cycle input exergy rate with different environment temperatures are shown in Figure 7. As Figure 7 illustrates it, the input exergy rate of dry air and water are inversely and directly proportional to the environment temperature, respectively.

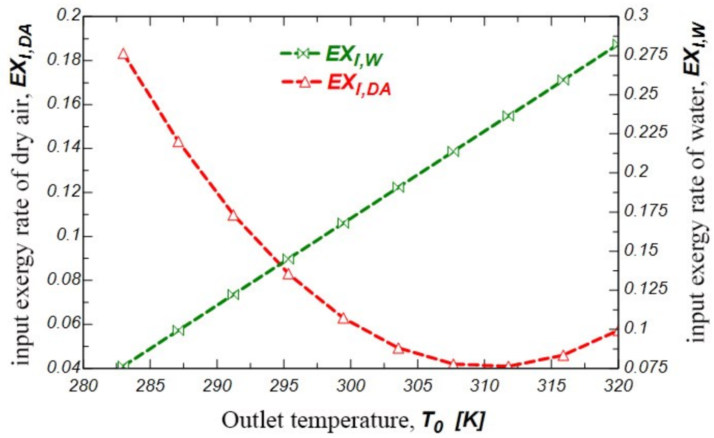

Fig. 7 The M-cycle input exergy rate of dry air and water

At 298 K (25°C) the input exergy rate of water is equal to 159.9 (Watt) and this value for dry air is equal to (69.34 Watt). The total input exergy rate (which comprises both water and dry air input exergy rate) in the M-cycle is equal to 229.24 (Watt).

The variations of the output exergy rate with different environment temperatures are shown in Figure 8. The environment temperature in the 5th climate is equal to 298 K (25°C) and the output exergy rate is calculated to be 32.34 (Watt). As Figure 8 illustrates it, the output exergy rate is directly proportional to the environment temperature.

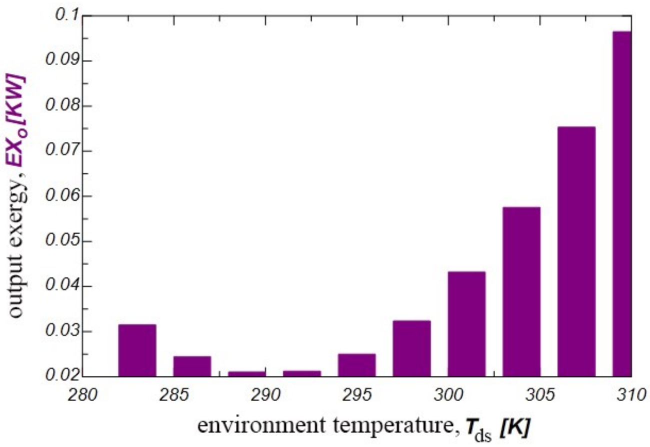

Fig. 8 The M-cycle output exergy rate

The variations of exergy loss with different environment temperatures are shown in Figure 9. The difference between the inlet and outlet air temperatures leads to exergy loss. As Figure 9 illustrates it, exergy loss is inversely proportional to the environment temperature. According to calculations, exergy loss rate at 25°C was found to be 93.23 (Watt).

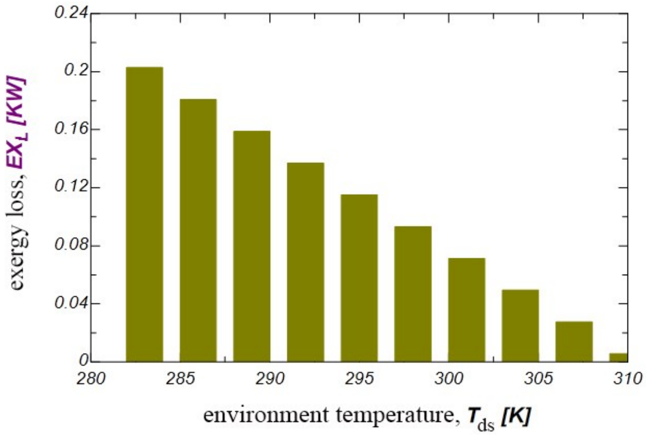

Fig.9 The M-cycle exergy loss rate

The variations of exergy destruction with different environment temperatures are shown in Figure 10. At 25°C the exergy destruction rate is equal to103.7 (Watt).

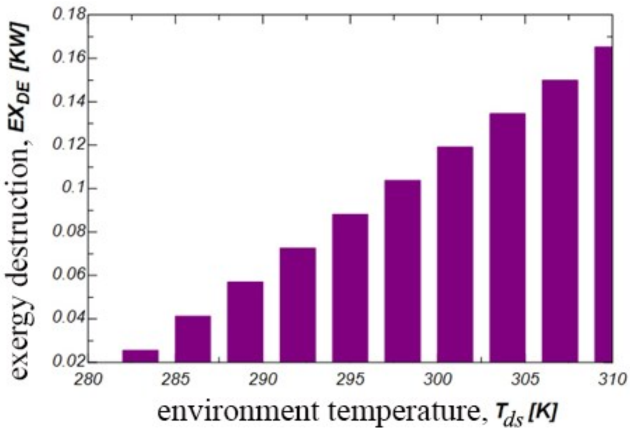

Fig 10 The M-cycle exergy destruction rate

Entropy generation of the system occurred during the exergy destruction. The variations of entropy generation rate with different environment temperatures are shown in Figure 11. The entropy generation rate is directly proportional to the environment temperature. At 25°C the entropy generation rate is equal to 0.0003479 (kJ/kg·K).

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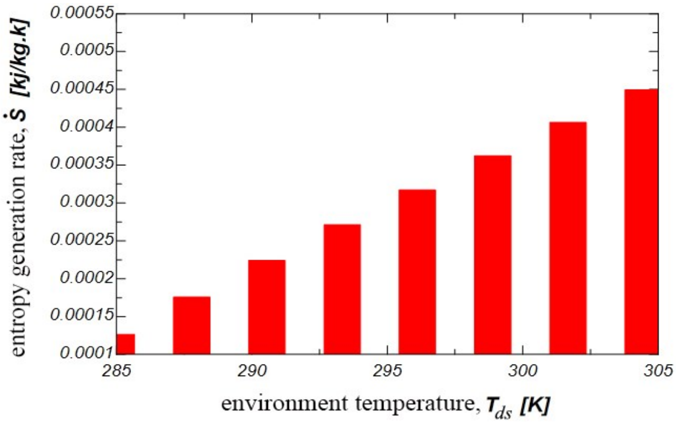
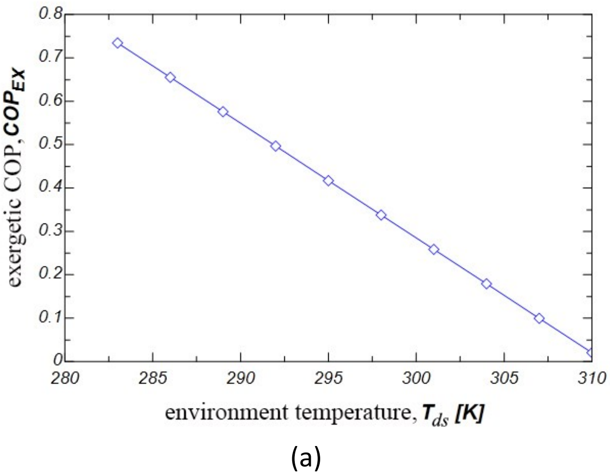


Fig 11 M-cycle Entropy generation rate

The variations of exergetic COP and exergy efficiency of the M-cycle with different environment temperatures are shown in Figures 12 (a) and 12 (b) respectively. At 298 K (25°C) the exergeic COP and exergy efficiency of the M-cycle are 0.3378 and 14.11 %, respectively. As Figure 12 (a) illustrates it, exergetic COP is extremely inversely proportional to the environment temperature, as at 283 K (25°C) the exergetic COP is equal to 0.74 and with an increase in environment temperature up to 308 K the COP will decrease to 0.1.

Exergy efficiency is the ratio between the obtained useful output exergy and input exergy and as indicated before, it is obtained by the equation (12). Environment temperature changes affect the output exergy (humid air exergy) so the exergy performance will change. As fig 12(b) illustrates an increase in environment temperature in the range from 295 K up to 305 K, leads to an extreme increase in exergy efficiency.



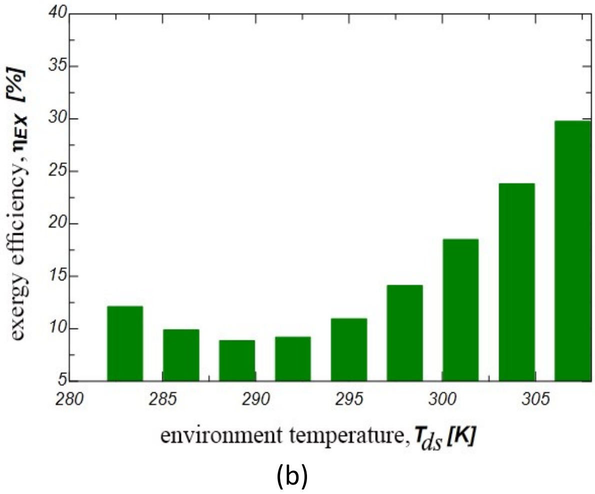


Fig. 12 (a) The exergetic COP rate of the M-cycle and (b) The exergy efficiency rate of the M-cycle.

The variations of exergetic COP with different dry bulb temperatures and variations of exergy efficiency with different dry bulb temperatures are shown in fig 13(a) and 13(b) respectively. As Figure 13(a) illustrates it, an increase in dry bulb temperature, leads to an extreme increase in exergetic COP. On the other hand, Figure 13(b) illustrates that an increase in dry bulb temperature, leads to an extreme decrease in exergy efficiency.

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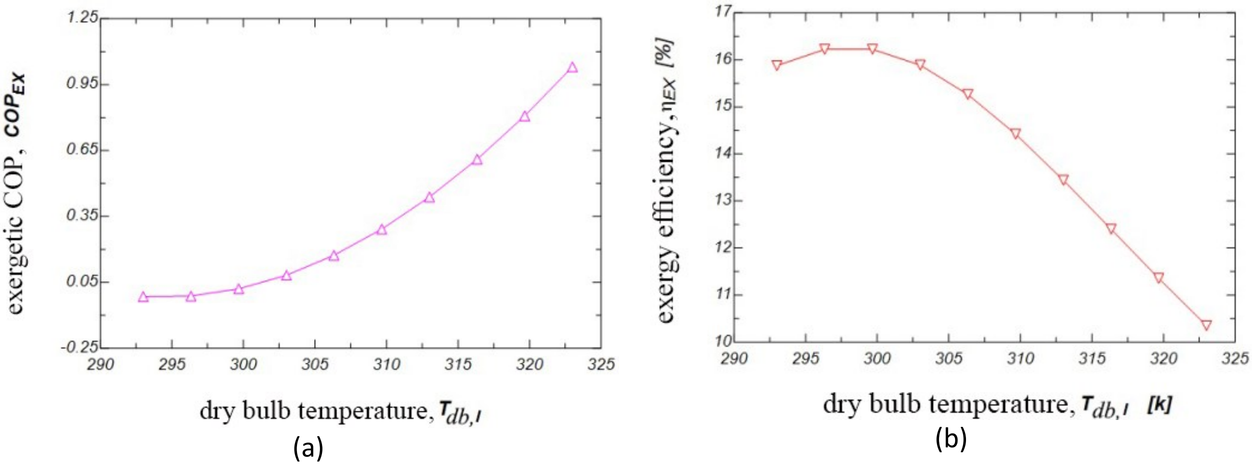

Fig. 13 (a) variations of exergetic COP with different dry bulb temperatures and (b) variations of exergy efficiency with different dry bulb temperatures.

The Grassmann's (exergy flow) diagrams of the m-cycle for 20°C and 25°C with 1 bar pressure are shown in Figure 14(a) and 14(b) respectively. Figure 16 shows that an increase in environment temperature from 20°C up to 25°C, leads to an increase of the exergy destruction rate and exergy output rate and on the other hand it leads to an extreme decrease of the exergy loss rate.

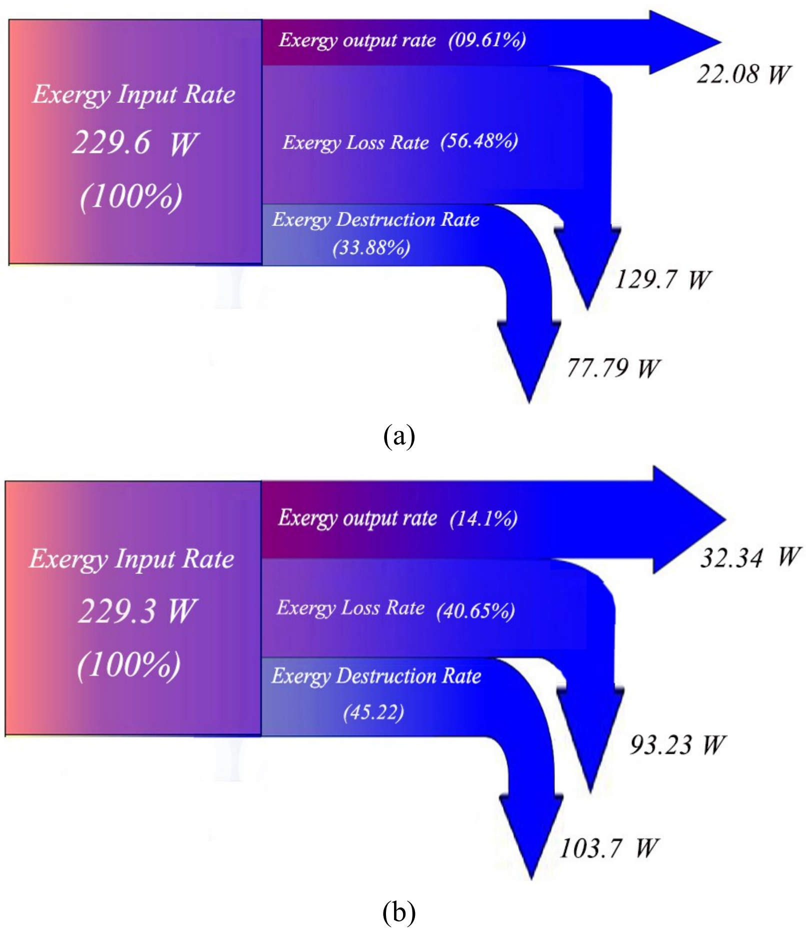

Fig.14 Grassmann's diagrams of the M-cycle at (a) 20˚C and (b) 25˚C.

The feasibility study of the M-cycle and water evaporation rate results are shown in table 7. With help of information from table 2, water evaporation rate and feasibility Index of the M-cycle were obtained.

Table 7. Water evaporation results and the M-cycle index

City (Province)	Climate Number	FI	FI_{dp}	V_w (lit/h)
Abadan (Ahvaz)	5	8.3	23.8	0.66
Isfahan(Isfahan)	9	1.1	32.6	0.46
Ahvaz(Ahvaz)	5	8.3	35.9	0.66
Bandar Abbas(Hormozgan)	6	20.2	12.7	0.44
Tehran(Tehran)	9	-1.2	31.6	0.44
Tabriz(East Azerbaijan)	3	1.3	28.3	0.29
Shahr kord (Chaharmahal Bakhtiari)	4	-1.2	29	0.32
Shiraz (Fars)	4	-0.1	33.3	0.34
Zahedan (Sistan and Baluchestan)	7	-0.1	36.1	0.34
Kerman (Kerman)	10	-2.2	36.9	0.33
Kermanshah(Kermanshah)	4	-2.2	36.2	0.33
Gorgan(Golestan)	2	12	16	0.29
Mashhad(Razavi Khorasan)	2	0.3	28.6	0.3
Ilam(Ilam)	5	3.6	27.4	0.21
Sari(Mazandaran)	1	21.6	5.1	0.2
Sanandaj(Kurdistan)	4	7.2	24.2	0.21
Yasuj(Kohgiluyeh and Boyer Ahmad)	4	4.9	22.5	0.2
Arak (Markazi)	9	6.5	21.5	0.2
Urmia (West Azerbaijan)	3	12.7	12.7	0.14
Ardabil (Ardabil)	3	17	6.8	0.21
Birjand (South Khorasan)	8	4.1	24.8	0.14
Zanjan(Zanjan)	9	11.2	15.7	0.21
Semnan (Semnan)	11	8	22.1	0.22
Qazvin (Qazvin)	9	10.7	17.3	0.23
Ghom (Ghom)	9	4.6	25.2	0.22
Hamedan (Hamedan)	4	9.1	17.7	0.23
Ramsar(Mazandaran)	1	22.9	3.9	0.23
Rasht (Rasht)	1	22.1	5.2	0.22

The results of direct evaporative cooling and dew point feasibility Index show that Ramsar, Rasht, sari and Ardabil cities the use of direct and indirect evaporative M-cycle cooling systems is not recommend due to very high relative humidity (approx. 80 %) and high temperature difference between the day bulb and dew Point (FI_{dp} less than 6°C), other hand Abadan, Isfahan, Ahvaz, Tehran, Tabriz, Shahr kord, shiraz, Kerman, Kerman shah, Mashhad, Ilam, Sanandaj, Yasuj, Arak, Birjand, Semnan, and Ghom cites have suitable condition for M-cycle. Gorgan, Uromia, Zanjan and Qazvin cities are at some hours of day suitable candidate for direct evaporative cooling and for use of the M-cycle cooling.

As previously indicated, water evaporation rate is assumed as a criterion for better performance of the M-cycle. In climates with acceptable FI_{dp} Index, the M-cycle has better performance in climates with lower water evaporation rate.

5 CONCLUSIONS

In this study energy and exergy analysis was made of the air cooling system based on the novel M-cycle system for eleven segmented climates of Iran. The main results of this work can be summarized as follows:

- Energy analysis shows that the 6th, 7th, 5th and 11th climates have in comparison with other climates higher values of cooling capacity, COP and dew point performance, respectively. This advantage provides a suitable condition for use of the M-cycle in the indicated climates
- Exergy analysis shows that the 6th, 7th, 5th and 11th climates have in comparison with other climates higher exergy efficiencies. Therefore, these climates have suitable condition for use of the M-cycle systems. Another result of this analysis shows that these climates have higher entropy generation rate and lower exergetic COP in comparison with other climates.
- The results of water evaporation rate of the M-cycle show that the highest water evaporation rate is equal to 0.66 lit/h in Abadan and Ahvaz cities.
- The overall results of the M-cycle feasibility study show that in almost all Iran climates with the exception of the north and north east cities of Iran, the use of the M-cycle is suitable.

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NOMENCLATURE

$\dot{\mathrm{E}}\mathrm{X}$	Exergy rate (kW)
e	Specific exergy (kJ/kg)
h	Enthalpy (kJ/kg)
$\dot{m}$	Mass rate (kg/s)
$\dot{\mathrm{Q}}$	Cooling capacity rate (kW)
T	Temperature (°C or K)
V	Evaporation rate (lit/h)
$\dot{W}$	Power (kW)
w	Moisture content (kg/kg)
ω	Humidity ratio (kg/kg)
ρ	Density (kg/m^3)
Greek Symbols	
ϵ	Effectiveness (−)
η	Efficiency (%)
Subscripts	
db	Dry-bulb
de	Destruction
dp	Dew-point
ds	Dead state
ex	Exergy
i	Inlet
l	Loss
o	Outlet
wb	Wet-bulb
wc	Working channel

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